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A review of the plastic value chain from a circular economy perspective

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ABSTRACT

Although plastic is one of the most commonly used materials in our everyday life, the current linear economy ('produce, use and dispose') engenders high risks to human health in relation to greenhouse gas (GHG) emissions and environmental pollution. As a response to these challenges, the circular plastic economy is gaining momentum, where the goal is to reduce, reuse and recycle all plastic. The transition to the circular economy should be made across the entire plastics value chain in order to ensure circular design, production, use and waste management. This study examines the current scientific literature in relation to the entire value chain of plastics. This aim of the article is to provide an overview of the existing research (and highlight research gaps) associated with the transition of plastic use to a circular model. The literature was divided into the following categories: 1) design; 2) production; 3) use; 4) end-of-life; and 5) value chain. A high proportion of the literature was found to address the end-of-life phase, suggesting that the other phases are currently neglected. The results have implications that are applicable to multiple phases; in particular, contamination of waste streams and composite materials places significant limitations on the opportunity to recycle and reuse plastic in new products. This calls for changes in the whole value chain, and for trans-sectorial collaboration to ensure systemic transparency. Therefore, future research should take a holistic approach to the transition to circular through careful mapping of implications, stakeholder involvement and collaboration.

1. Introduction

Plastic is one of the most commonly used materials in our everyday life (Eriksen et al., 2020). In 2019 alone, Europe consumed approximately 50.7 m tons (PlasticsEurope, 2020). Plastic is used in many industrial processes, products and packaging, owing to its being comparatively inexpensive, light, mouldable and durable (Bishop et al., 2020; Heller et al., 2020). Although the use of plastic in products and packaging comes with many economic and societal advantages, the extent of its use creates environmental risks related to greenhouse gas emissions (GHG) and environmental pollution (European Commission, 2018; Hahladakis et al., 2018). It is estimated that 4.8m–12.7 m tons of plastic is lost to the environment every year (Jambeck et al., 2015) and, in 2015, emissions from the incineration of plastic packaging reached about 16 m tons of CO_2 equivalents (CIEL, 2019).

The linear flow of plastic through the value chain is one of the primary current sources of CO_2 emissions and environmental pollution. A significant portion of plastic is used only once in products and packaging, with only a limited amount being reused or recycled (Dijkstra et al., 2020). In Europe, 31% of all plastic waste is sent to landfill, while 39% is incinerated and, although the rate of landfilling is decreasing, incineration rates are increasing, rather than pivoting towards recycling or reuse (European Commission, 2018). However, as a response to these negative consequences of the linear plastic value chain and 'throw-away' culture, the circular economy is gaining momentum and more countries, businesses and international associations are developing strategies for a transition to the circular economy, targeting increased reuse and recycling of plastic (see, e.g., Ellen MacArthur Foundation, 2020; European Commission, 2020).

The circular plastic economy is a viable alternative to the existing linear system, wherein plastic is produced, used and disposed of. The purpose of the circular economy is to increase the amount of plastic that is reused or recycled back into the system (Calleja, 2019; European Commission, 2018). A circular plastic economy could contribute to less plastic being downcycled, incinerated and landfilled, and contribute to making plastic waste a resource for new products in a closed-loop

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production and consumption system. Despite the circular economy gaining increasing levels of attention, only 30% of plastic waste is collected for recycling in Europe and most of the waste is downcycled into materials with a lower value than that attributed to the original product (Calleja, 2019). The downcycling of plastic in the economy is caused by contamination with organic and inorganic matter, and from product designs that combines different polymer types and thereby inhibit and complicate technical and economically feasible pathways for plastic-waste recycling (M. T. Brouwer et al., 2018; Dahlbo et al., 2018). This is a particular challenge in relation to post-consumer plastic waste, which typically consists of a diverse mix of different polymer types and additives, often generated from short-lifespan products and single-use plastic packaging materials. Existing research has examined how to recycle post-consumer plastic, clean it, sort the polymers and recycle contaminated plastic waste (e.g., Gasde et al., 2021; Kranzinger et al., 2018; Meys et al., 2020). According to M. T. Brouwer et al. (2018), however, the cause of mixed polymers in recycling is not only sorting and recycling processes but the initial design of plastic products and packaging. Packaging and other post-consumer plastics are often designed with multiple polymers, which makes recycling difficult from a technical as well as an economic perspective.

The transition towards a circular economy, therefore, cannot be achieved solely through changes within the waste-handling system but must be combined with changes in other parts of the value chain, including the design, the production and the phases. This creates a societal need to develop the knowledge base to support the transition, where the full value chain of plastics is studied to examine how to design, produce, use and recycle plastic within the circular economy. The existing knowledge base tends to emphasize research focused on the 'end-of-life' phase, aimed at improving recycling and recovery of plastic waste (Nielsen et al., 2020). However, a significant amount of the new research focuses on other phases of the value chain, particularly the design phase (e.g., Network for Circular Plastic Packaging, 2020). The increased attention given to the circular economy in recent times has seen a concomitant increase in research with a value-chain focus and the recognition of the importance of a more holistic approach.

The aim of this study is to provide an overview of the existing research and research gaps associated with the creation of a circular plastic economy. The study is based on a systematic, critical approach; the literature is reviewed through a systematic database search with different combinations of keywords.

2. Methodology

The concept of the circular economy is used as the framework for structuring the study. Fig. 1 illustrates the plastic value chain and the search terms used, based on the framework. The methodology used in this article is based on traditional methods for conducting systematic and critical reviews. A systematic review is often used in medical science and is, for example, conducted in alignment with the requirements of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Moher et al., 2009), which includes a systematic literature search and documentation of included and excluded studies. The PRISMA Statement includes a 27-point checklist and a template for flow of information through the review (Moher et al., 2009). Inspired by this approach, the literature in our study was managed through a structured database search, using pre-selected search words. The papers from these searches were then screened for duplicates and irrelevance. The relevance of the papers was assessed based on three inclusion criteria: 1) the value chain of plastic as the main topic of interest; 2) primarily post-consumer plastic or plastic in general and, therefore, a delimitation of alternative types and uses of plastic (such as bioplastic, plastic in Waste from Electronic and Electrical Equipment (WEEE) products, etc.); 3) plastic in the circular economy. Lastly, a decision was

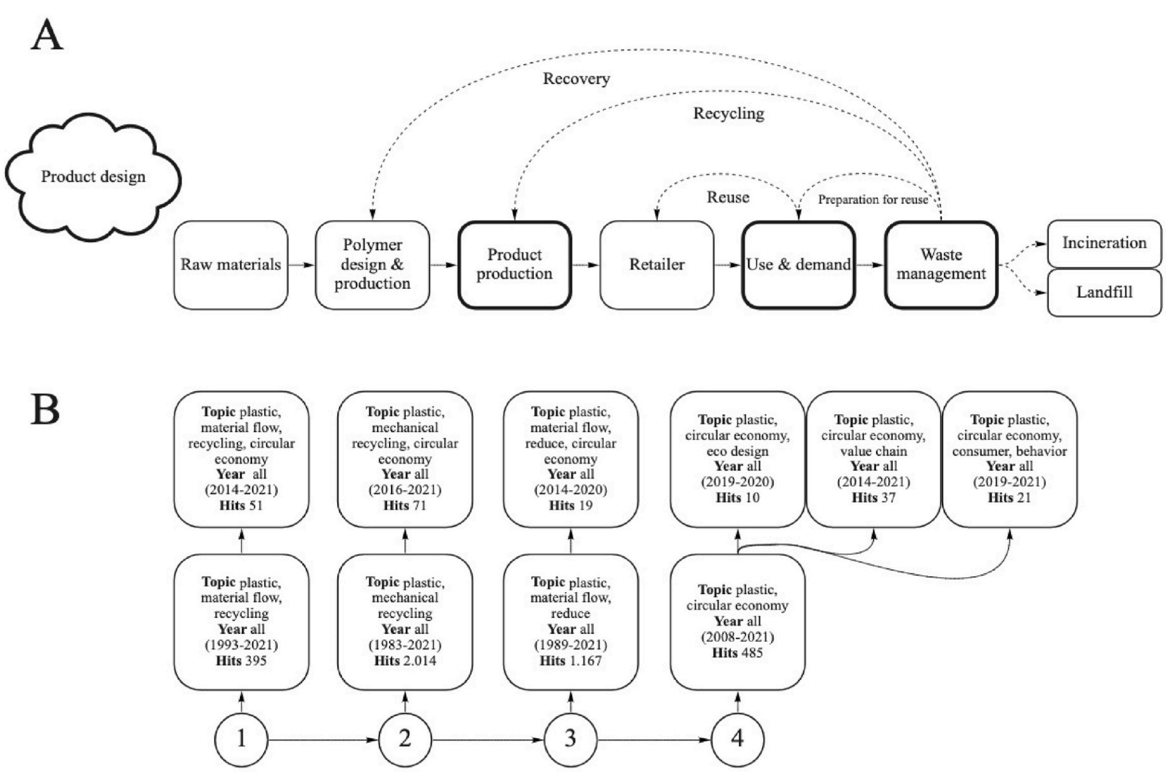

Fig. 1. A: The marked boxes indicate the value-chain phases that are the main focus, owing to these phases being a part of the primary loops of the circular economy, where the key principles are to reduce, reuse and recycle resources and products back into the system (Kirchherr et al., 2017). Fig. 1B: Iterations, keywords and output from the literature search in Web of Science database. The figure shows the four overall iterations (1–4) and the keyword compositions to narrow the amount of hits.

made to include only research relevant to a European context.

The literature search was carried out using the Web of Science database through four overall iterations between January and May 2021. The following keywords were used, both alone and in combinations, as illustrated in Fig. 1B: 1) plastic, 2) material flow, 3) recycling, 4) circular economy, 5) reduce, 6) value chain, 7) consumer behaviour and 8) eco design. During the first three iterations, the papers were selected from the period 1983–2021; subsequently, the search was narrowed by including 'circular economy' in keywords, and the timespan was adjusted to 2008–21, in alignment with the approximate timeframe in which the circular economy has come to prominence as a subject for scientific and public discussion.

Through the database search, 211 papers were initially identified. These were further screened for relevance by reading abstracts and main findings, which reduced the number of relevant studies to 74. Afterwards, all studies were analysed through full-text readings, which further decreased the number to 60 relevant studies. The reason for excluding papers from the review was primarily owing to the fact that the papers did not meet the overall inclusion criteria as described above (in particular, criteria 2).

In processing the results from the literature search, the papers were divided into four overall value-chain phases: 1) design, 2) production, 3) use, 4) end-of-life. An additional, fifth category was added, which included the entire value chain, in order to account for the studies that included more than a single part of the value chain.

3. Result and discussion

3.1. Research along the value chain

The results of the literature search show an unequal distribution of research across the different phases of the value chain. As illustrated in Fig. 2, the majority of published articles focus on the waste-management phase, with a comparatively small number of studies dealing with product design, production, and use. This highlights an important knowledge gap, as most research has been focused on the end-of-life phase, despite increased political and scientific emphasis on the circular economy that, ideally, would include recycling as just one aspect of an overall strategy (see, for example, Kirchherr et al. (2017), who suggests a circular-economy typology consisting of nine strategies, where recovery and recycling belong to the least emphasized strategies in a circular economy context).

In order to provide an in-depth, systematic overview and discussion of the literature, the results are presented and discussed in sections structured in alignment with the overall categorization.

3.2. Design

Design is the initial phase of the value chain. It is during the design phase that the function and qualities of the product are decided (e.g., colour, recyclability, polymer mix) (Iacovidou et al., 2019). Five of the 60 articles examine how to design packaging so that less plastic is used, or so that recycled plastic can be a part of the design. The focus of the studies in the design-phase literature varied depending on the aim of the individual study; that is, whether to reduce the amount of plastic (Foschi et al., 2020); to design products with recycled plastic (Civancik-Uslu et al., 2019; Masmoudi et al., 2020); or to design products that are recyclable after end-use (Gall et al., 2020; Iacovidou et al., 2019). A common theme in the literature is the challenge of designing packaging (specifically food packaging) with less plastic or with recycled materials. This is owing to the high quality standards with which food packaging must comply, including low migration of toxins; being light-weight; and having the ability to keep food fresh (Masmoudi et al., 2020).

Additionally, the research in this category concludes that recycled plastic can be difficult to use in new products owing to the contamination of polymer types, which may affect aspects such as durability, toxicity and weight (Civancik-Uslu et al., 2019; Foschi et al., 2020; Gall et al., 2020; Iacovidou et al., 2019; Masmoudi et al., 2020). When trying

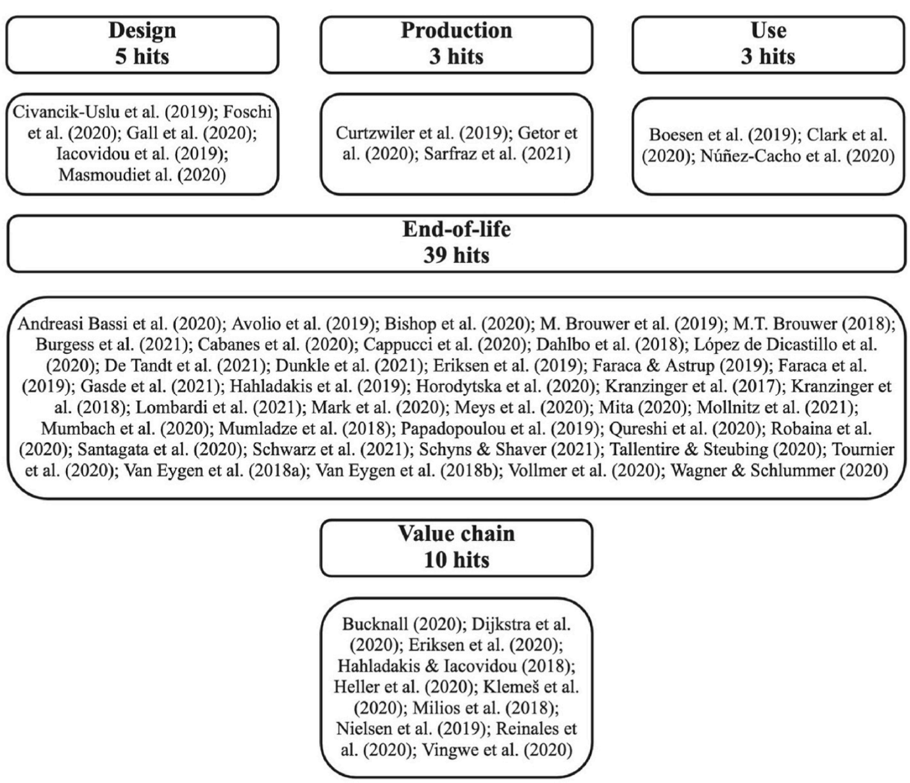

Fig. 2. Division of literature representing the different phases of the value chain of plastics. Categorization is made according to the phase in the value chain that the individual study examines. Five categories were designated, including both the phases of the value chain and the studies dealing with the whole value chain.

to incorporate recycled plastic into new products, contamination and mixed polymers are, according to Gall et al. (2020) and Iacovidou et al. (2019), two of the most problematic impediments. These two studies explored the opportunity to use recycled materials in the production of new polyethylene terephthalate (PET) bottles. Both studies concluded that the entire value chain must be considered and that products should be designed with fewer polymer types, which can be looped back into the circular system. All five studies show that some of the challenges can be overcome by incorporating the whole value chain of plastics into the design of new products, to ensure better production, use, and recyclability (Civancik-Uslu et al., 2019; Foschi et al., 2020).

The literature shows that there are a number of principles to follow when designing out waste while ensuring recyclability of products, including: 1) slowing resource loops through the design of long-life goods and product-life extension; 2) closing resource loops through recycling; 3) design for sustainable sourcing; 4) design for optimized resource use; 5) design for environmentally sound and safe product use; 6) design for prolonged product use; and 7) design for recycling (inspired by Bocken et al., 2016; le Blevennec et al., 2018).

3.3. Production

The production phase covers multiple production steps and traditionally includes the melting and moulding process of primary plastics (crude oil mixed at high temperatures to produce plastic polymer) into different plastic products (Getor et al., 2020). This phase has several implications when it comes to incorporating recycled post-consumer plastic into the plastic mixture. Three of the 60 papers address this phase of the value chain, where the primary focus is successfully mixing recycled plastic with virgin plastic (Curtzwiler et al., 2019; Getor et al., 2020), and the possibility of producing food packaging with nanocomposites to make the production more sustainable (Sarfraz et al., 2021). A common aspect of the studies by Curtzwiler et al. (2019) and Getor et al. (2020) is that they highlight a range of challenges when using recycled plastic in manufacturing processes.

One of the most significant challenges is that the recycled plastic is most often composed of different polymer types and contaminated with non-plastic materials, such as additives. This causes a range of complications (e.g., lumps of undispersed crystalline plastic, which reduces the value of the final product (Getor et al., 2020)). Additionally, Curtzwiler et al. (2019) concluded that recycled polyolefins have a significant impact on the physical properties of virgin polypropylene. As an approach to overcoming these challenges, both studies examine whether it is possible to mix virgin and recycled plastic, and which mix ratio is most effective. However, according to Getor et al. (2020), one of the biggest challenges when using recycled plastic is to identify polymer type and other contaminations. This has a significant impact on the possibility of using recycled plastic in the production process. There is no solution to this dilemma currently available, which implies that solutions must be found in other phases of the value chain. If plastic products are designed with mixed polymers or contaminated in the waste (collection and sorting) and the waste stream becomes contaminated, the properties of the recycled plastic will be affected (Getor et al., 2020). The literature that addresses the circular production of plastic goods is not only concerned with recycled plastic. Sarfraz et al. (2021) examined the possibility of using nanocomposites in the plastic mixture to accommodate the transition to circular; however, owing to a lack of research in the field, it is not yet possible to conclude whether introduction of nanocomposites will make recycling easier (Sarfraz et al., 2021).

3.4. Use

The third phase of the value chain is consumption, addressing the demand, use and disposal of plastic products. Three articles address this phase: two that address the purchase and demand (Boesen et al., 2019; Núñez-Cacho et al., 2020) and one that focuses on post-consumption handling of plastic (Clark et al., 2020). The three studies in this phase highlight a range of implications in the use phase. The gap between the actual environmental impact and consumer perception of that damage is, according to Boesen et al. (2019) and Núñez-Cacho et al. (2020), a major hindrance to the transition to circular. To overcome this, consumers must be better informed about the environmental impact of the goods they are purchasing. However, Núñez-Cacho et al. (2020) concluded that 69% of consumers worry about the impact of plastic on the natural environment, illustrating a general awareness of plastic pollution. When purchasing products, consumers are influenced by habits, beliefs, knowledge and social norms, which impact consumer demand for plastic products (Núñez-Cacho et al., 2020). Clark et al. (2020) take a more holistic approach to the use phase of the value chain, declaring that the user is paramount when it comes to both the design of new products and increasing recycling rates. According to Clark et al., behavioural transition is crucial to the success of the circular economy, owing to the consumer's role in both creating demand for and sorting the plastic after use. It is, therefore, important to take this aspect into account when designing solutions for the whole value chain. A challenge is that involvement of other phases is not a part of the current workflows of the value chain and changing consumer behaviour can be difficult.

3.5. End-of-life

The final phase, end-of-life, involves both sorting and recycling of the plastic waste. An important aspect of the circular economy is looping the waste flow back into the production of new products and services. The end-of-life phase is, therefore, an important phase in the circular economy (Bucknall, 2020). More than half of the studies (39 of 60) deal with this phase. Owing to the high number of studies concerning this phase, this section is the most elaborate. The studies included in this review are categorized according to the main topic of each paper. The categories are 1) collection and sorting; 2) recycling technologies (mechanical, chemical, biological); 3) lifecycle assessment (LCA) and mass flow analysis (MFA) (of the end-of-life phase); and 4) policy and regulation.

3.5.1. Collecting and sorting

The initial phase of waste management is collecting and sorting; four papers address this phase. Different collection and sorting solutions are presented, such as separate waste collection (e.g., a "catch all plastics bin" (Burgess et al., 2021; Kranzinger et al., 2017; Tallentire and Steubing, 2020) and tracer-based sorting (Gasde et al., 2021). Separate waste-collection systems are presented in the literature, examining ways to improve recycling rates for plastic waste (Burgess et al., 2021; Kranzinger et al., 2017; Tallentire and Steubing, 2020). Burgess et al. (2021) studied plastic-waste-collection systems in the UK and developed their vision of a collection system wherein all plastic waste is collected through a standardized, single-bin collection system (as opposed to the current multi-bin, curb-side collection system, where the plastic waste is further sorted at Material Recovery Facilities and eventually mechanically recycled or incinerated in waste-to-energy plants, often outside the UK) and afterwards recycled using a combination of chemical and mechanical technologies.

According to Burgess et al. (2021), the so-called "one-bin-to-rule-them-all" system could increase collection rates and reduce the post-use leakage of plastic waste into the environment, but the effectiveness of the system would require infrastructure that supports the transition to circular, including mechanical and chemical recycling technologies; recyclable product design; and sorting systems. Kranzinger et al. (2017) and Tallentire and Steubing (2020) agree that there is a need for a holistic approach to plastic design and waste management, to improve the collection of plastic waste. The authors argue that a separate waste-collection system would allow improved communication with the consumer, in turn making it easier to manage the plastic waste (Kranzinger et al., 2017). In relation to the sorting of plastic waste, one paper examines the opportunity for tracer-based sorting (Gasde et al., 2021). Tracer-based sorting would make it easier to sort plastic according to polymer types and, therefore, would produce less contamination, but this also requires the incorporation of marking into the design and production process.

3.5.2. Recycling technologies

The literature on waste management primarily explores recycling technologies, including mechanical recycling (Avolio et al., 2019; Cabanes et al., 2020; Dahlbo et al., 2018; de Tandt et al., 2021; Eriksen et al., 2019; Kranzinger et al., 2018; López de Dicastillo et al., 2020; Mita, 2020; Möllnitz et al., 2021; Schyns and Shaver, 2021); chemical recycling (Dunkle et al., 2021; Mark et al., 2020; Meys et al., 2020; Mumbach et al., 2020; Mumladze et al., 2018; Qureshi et al., 2020; Santagata et al., 2020; Tournier et al., 2020; Vollmer et al., 2020); and biological recycling (Papadopoulou et al., 2019). Derived from the ISO15270:2008 standard and ASTM D7209 definitions, Schyns and Shaver (2021) identified four overall types of recycling, as illustrated in Fig. 3., which indicates the priority of recycling technology according to the quality of recycled and recovered plastic.

The articles discuss how a combination of mechanical and chemical recycling is a part of the transition to circular but considers mechanical recycling to be the main recycling technology (Schyns and Shaver, 2021). In relation to mechanical recycling, both potential barriers and opportunities are identified. Packaging and municipal waste are seen as good sources of plastic for recycling, but mechanical recycling is impeded by contaminated waste streams, which, in a mechanical process, can affect the properties of the recycled plastic (Avolio et al., 2019; Dahlbo et al., 2018; Eriksen et al., 2019; Möllnitz et al., 2021). Multiple strategies to overcome these challenges are examined in the research, including wet mechanical recycling (Kranzinger et al., 2018) and upstream washing processes (Möllnitz et al., 2021). Furthermore, according to López de Dicastillo et al. (2020) and Schyns and Shaver (2021), changes in polymer length and mechanical properties are major challenges encountered in mechanical recycling of plastic waste. This issue is difficult to overcome because it affects the overall quality of the plastic. Some of the identified opportunities to overcome this challenge when using recycled plastic in production of new products and packaging is either to mix the recycled plastic with virgin plastic or, as López de Dicastillo et al. (2020) investigates, to mix in nanoadditives.

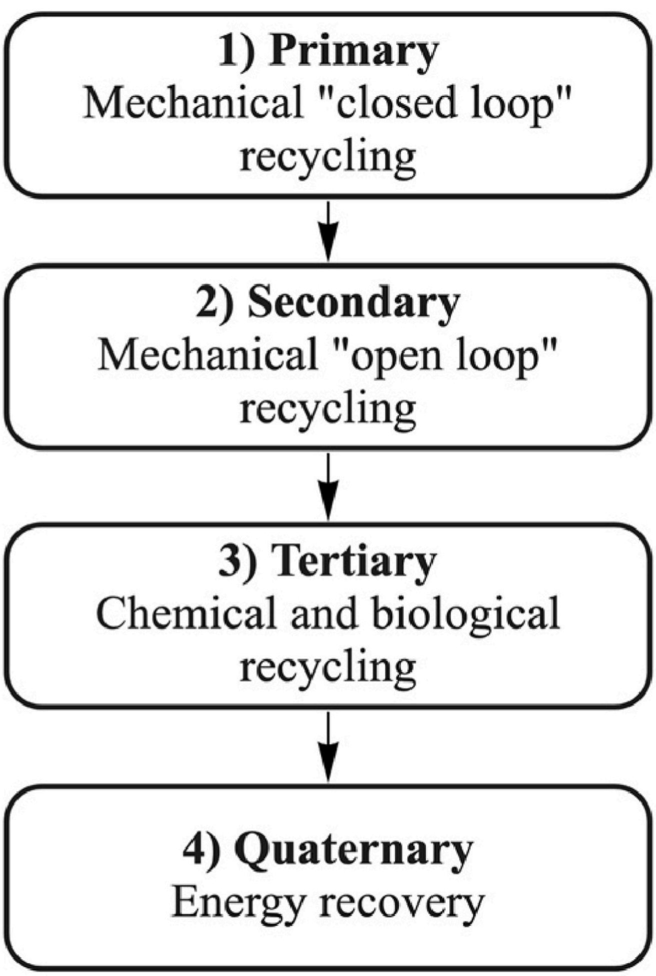

Fig. 3. The four general types of recycling, in order of prioritization according to both environmental and circular value. Adapted from Schyns and Shaver (2021).

Another recycling technology that is explored in the literature is chemical recycling, which is suggested as a technology to facilitate the transition to circular (Meys et al., 2020; Vollmer et al., 2020). Chemical recycling is seen as an addition to the current recycling technologies to allow recycling of plastic that cannot be recycled mechanically, such as composite materials (Dunkle et al., 2021; Qureshi et al., 2020). The main advantage of the chemical-recycling technology is its ability (in combination with mechanical recycling) to increase overall recycling rates, despite a series of identified technical difficulties associated with the technology. Contamination and the mixture of several polymers can, in chemical recycling, also have a negative impact on the recycled plastic (Mark et al., 2020). Sorting and cleaning are, therefore, seen as an important part of most recycling processes (Vollmer et al., 2020). However, most studies show that chemical recycling is an advantage when recycling multilayer packaging or composite plastic (Mumladze et al., 2018). Depending on polymer type and chemical process, the recycled material may retain its properties; chemical recycling is, therefore, seen by some authors as a solution to the issue of plastic-waste mismanagement (Mumladze et al., 2018; Santagata et al., 2020; Tournier et al., 2020). The last type of recycling technology examined in the literature is biological recycling. Only one paper addresses this. According to Papadopoulou et al. (2019), biological recycling has potential, but must be further developed to make a viable contribution to the circular economy.

3.5.3. LCA and MFA to explore recycling pathways

The third category of the end-of-life phase is composed of articles that use lifecycle assessment (LCA) and mass flow analysis (MFA) to study, explore and compare recycling pathways. In the 13 papers addressing this category, several implications are identified for the end-of-life phase; implementationof LCA and MFA is also presented. Firstly, owing to a lack of data, the studies find it challenging to achieve an adequate estimate of the material flow and environmental impact in the end-of-life phase (Andreasi Bassi et al., 2020; Bishop et al., 2020; Lombardi et al., 2021). In relation to the LCA of different recycling technologies and the environmental impact of mechanical and chemical recycling, Faraca and Astrup (2019) concluded that mechanical recycling has the lowest environmental and financial impact but, if most plastic is to be recycled, a mix of mechanical and chemical recycling will be necessary. van Eygen et al. (2018b) also conclude that mechanical recycling of plastic can contribute to reduction of GHG emissions.

According to Schwarz et al. (2021), the quality and performance of recycling technologies depends on polymer type and mix. Polymers of poor-quality and mixed plastics are, therefore, better managed with chemical recycling technologies. Nevertheless, closed-loop mechanical recycling, sorting and collection must also be improved (Horodytska et al., 2020; Schwarz et al., 2021). To increase the recycling rates in Europe, it is necessary to improve both collection and sorting, to ensure the availability of larger amounts of plastic waste for recycling, but also to increase the quality of the recycled plastics (M. T. Brouwer et al., 2018; Hahladakis and Iacovidou, 2018; Horodytska et al., 2020; van Eygen et al., 2018a). The design of plastic packaging is another important factor often mentioned in the literature in respect of improving recycling rates (M. Brouwer et al., 2019; M. T. Brouwer et al., 2018). According to Faraca and Astrup (2019), most plastic collected for recycling is coloured plastic originating from products with a short lifespan (e.g., packaging), which affects recyclability. Regulation and legislation in relation to sorting, collection and recycling are suggested by researchers as a solution to some of these challenges (Bishop et al., 2020; Horodytska et al., 2020).

3.5.4. Regulation and legislation

Regulation and legislation is the fourth and last category of literature identified in relation to the end-of-life phase. According to Robaina et al. (2020), variations in how countries manage plastic waste are primarily owing to different rates of economic growth and the opportunity to invest in recycling technologies. Government policy must, therefore, facilitate investment in the transition to circular and economically support private investors (Robaina et al., 2020). Policy and investment are, according to Wagner and Schlummer (2020), also an important part of ensuring that hazardous chemicals in plastic designed out of new plastic products and packaging.

3.6. Value chain

As this review examines the literature in the context of the whole value chain of plastics in relation to the circular economy, a fifth category was made to include literature with a value-chain approach to researching plastic in the circular economy. Ten of the 60 papers address more than one aspect of the value chain. The papers have different approaches to the concept of the value chain of plastic and the circular economy. The different approaches include: 1) general and theoretical aspects of plastic (Bucknall, 2020; Hahladakis and Iacovidou, 2018; Milios et al., 2018; Nielsen et al., 2020); 2) LCA & MFA (Eriksen et al., 2020; Heller et al., 2020; Klemeš and Fan, 2021; Reinales et al., 2020; Vingwe et al., 2020); and 3) sustainable business models (Dijkstra et al., 2020).

To reduce the amount of waste and pollution from plastics, it is crucial to study not only how to recycle plastic but also how to create a circular value chain. According to Bucknall (2020), the focus should be on how to create a circular plastic economy to avoid plastic pollution, not only through recycling, but also design, use and legislation. To ensure homogeneity of plastic waste, which can be optimally recycled, it is not only crucial to have the right recycling facility but also to design, produce, use and dispose of the materials so that closed-loop recycling is possible (Eriksen et al., 2020; Nielsen et al., 2020). An identified challenge is that regulation and legislation are focused on specific phases of the value chain or environmental pollution, which means that other important factors are not addressed (Hahladakis and Iacovidou, 2018; Nielsen et al., 2020). According to Nielsen et al. (2020), most legislation is about regulating the end-of-life phase (e.g., waste-management legislation), paying little attention to the remaining phases. This, according to (Dijkstra et al., 2020), is also a problem in the current research about circular business models, where the majority of the research focuses on the recycling of plastic, leaving out other aspects of the circular plastic economy.

Another challenge mentioned is that the existing literature focuses on recycling and reducing the amount of plastic consumed, rather than on reuse (Klemeš and Fan, 2021). Furthermore, the focus should not only be on how to change consumer habits, but also to regulate the manufacturer, so that more recyclable and reusable plastic products are developed and marketed (Klemeš and Fan, 2021). Other ways of examining the value chain of plastic is through lifecycle- and material-flow analysis, and for these studies the lack of data representing the whole value chain is a major challenge (Heller et al., 2020). However, an overview of the material flow, environmental, economic, and social impact can give a foundation for better business decisions and policymaking (Reinales et al., 2020; Vingwe et al., 2020). According to Milios et al. (2018), some of the opportunities to overcome the value-chain implications are to have better communication between value-chain phases and stakeholders, and for consumers (especially through public procurement) to demand recyclable plastic and a transparent value chain.

4. Implications and research gaps

A range of implications are emphasized in the research across the value chain of plastics. Fig. 4 summarises the main challenges in each value-chain phase. The figure indicates that solutions to the identified challenges will probably require a holistic approach, both in and between the phases. This is especially evident in the challenge regarding composite materials and contamination of recycled plastic, which reoccurs in three of the five categories, affecting both the design, production and end-of-life phase, owing to the limited possibilities to recycle the plastic into products of the same value and quality (Civancik-Uslu et al., 2019; Curtzwiler et al., 2019; Foschi et al., 2020; Gall et al., 2020; Getor et al., 2020; Iacovidou et al., 2019; Masmoudi et al., 2020). Contamination of plastic waste streams has different implications according to which value-chain phase the challenge occurs within. As illustrated in Fig. 4, contamination in the design and production phase causes difficulties with designing and making products and packaging with recycled materials, because it affects the overall quality of the product or packaging. In the end-of-life phase, contamination affects the recycling opportunities, causing technical and economic constraints on recycling. This indicates that collaboration and research that address the interrelation between the phases is required, in order to ensure that the processes in one phase do not hinder circularity in another.

However, the transition to circular not only relates to how to recycle or redesign plastic products. A reduction in the amount of plastic used and sorted is another key challenge. For this aspect, Clark et al. (2020) pointed towards changes in behaviour and user involvement as one of the greatest obstacles to reducing and recycling plastic waste.

The review of the literature suggests that the transition to circular must involve more than new recycling technologies; it must also involve rethinking the way we design, produce and use plastic products (Iacovidou et al., 2019). This approach is highlighted in most studies (including the current one) but is not reflected in the number of studies covering each value-chain phase. According to Milios et al. (2018), one of the hotspots found in the value chain is lack of communication and coordination, which results in lack of traceability. This indicates that the lack of co-ordination and knowledge of the remaining phases within the value chain affects the whole system. As stated above, studies focusing on the entire value chain conclude that current policy and research focuses primarily on end-of-life (Hahladakis and Iacovidou, 2018; Nielsen et al., 2020), neglecting the other important phases and how these may impact end-of-life possibilities for reuse and recycling.

According to Eriksen et al. (2020), changes in plastic design, demand and collection have a significant impact on the end-of-life possibilities for plastic and the opportunities to recycle the plastic into new products. This indicates that a holistic value-chain approach, where trans-sector collaboration is a key component, is necessary to ensure an efficient and effective transformation of the current linear plastic value chain. However, the proportion of the literature covering each value-chain phase indicates a knowledge gap in the design, production and use phase. This knowledge gap may hinder both the transition to circular and the operation of waste-management procedures 'symptom treatment' in the end-of-life phase, with limited attention consequently given to opportunities for redesign and prevention of plastic waste, despite the fact that these aspects are often regarded as the most desirable in the circular-economy literature (Kirchherr et al., 2017). The circular economy has frequently been criticized for not having a clear definition and for giving companies the bare minimum recycling rate (Nielsen et al., 2020). This could be at least partially addressed through a consideration of the entire value chain, rather than merely on the end-of-life phase.

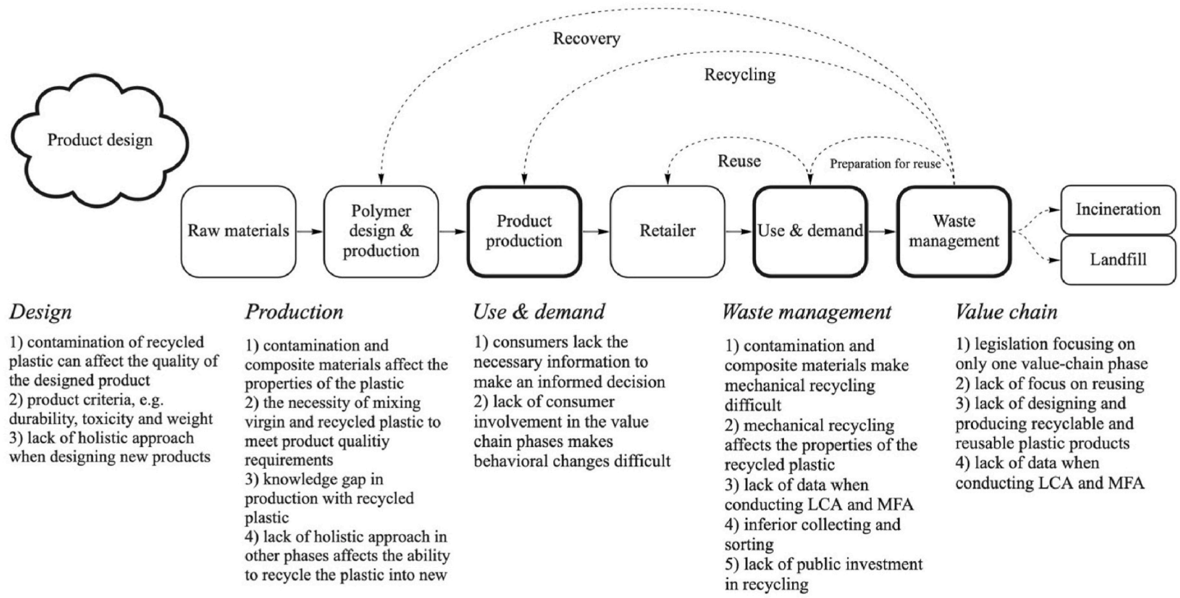

Fig. 4. The main challenges in the value-chain phases: design, product production, use & demand, waste management, and a category for the entire value chain.

5. Conclusion

The circular plastic economy has gained momentum, but there is still an imbalance in the amount of literature addressing the challenges and opportunities that would come with a transition to a circular economy in all the value-chain phases: 1) design, 2) production, 3) use, and 4) end-of-life. There is a predominance of studies in the literature in the end-of-life phase, examining the implications and solutions for collection, sorting and recycling of plastic waste. This leaves a smaller amount of literature addressing the remaining phases, leading to research gaps associated with design, production and use of plastic. Despite the major research focus on end-of-life, the review identified challenges that occur in more than one phase. The most commonly identified challenge is the contamination of plastic waste and the widespread use of composite materials in plastic products and packaging. This implicates the use of recycled plastic in the design and production phase and makes it technically and economically difficult to recycle in the end-of-life phase. Another major challenge is the lack of a holistic approach that can identify challenges and solutions across the phases in the plastic value chain. This challenge is mentioned in the literature but is also reflected in the proportion of studies in each phase.

Particular problems are caused by workflows and behaviour in other phases, such as the design of composite products or deficient sorting of plastic waste, potentially causing contamination in the recycling process. Potential solutions to these challenges to circularity could be to integrate design for recycling; include recycled materials in the production process; increase the demand for recyclable materials; reduce the use of plastic products; and raise investment in the development of recycling technologies (and technology systems that integrate or combine mechanical and chemical recycling technologies). These solutions could contribute to the transition to a circular economy by keeping plastic resources within the closed-loop consumption and production system. However, this transition will not happen without further research in each phase and collaboration across the value chain, to prevent implications both within each phase, and also affecting other phases. The literature examined in this review calls for additional research into design, pure waste streams and modified consumer behaviour. Future research should take a holistic approach to the transition to circular. This can be done through mapping of the implications, identifying where in the value chain these occur, and promoting stakeholder involvement and collaboration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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